Further Results from AMPS Modeling of Stress Effects on the CdS/CdTe Solar Cell

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ABSTRACT

This paper reports the application of AMPS simulation to a specific group of experimental CdS/CdTe solar cells that have undergone various degrees of stress, with J-V curves ranging from normal behavior to severe rollover. Experimental data such as C-V measurements of carrier density profiles are also incorporated into the modeling of these cells. The results show that rather small changes in the back contact barrier height (~ – 0.03 eV) are sufficient to qualitatively duplicate the effects of stressing on the J-V curves. The mechanism for rollover is also elucidated with recombination profiles.

1. INTRODUCTION

Past modeling efforts [1] with AMPS [2] have enabled us to simultaneously duplicate the J_{sc}, V_{oc}, ff, efficiency, and spectral response data for certain champion CdS/CdTe cells almost exactly, using a combination of experimental data and physically reasonable parameters. The modeling also qualitatively explained the non-ideal J-V behavior (rollover, crossover, V_{oc} shift, and rollunder) observed as a result of stressing CdS/CdTe cells.[3] Qualitative agreement between simulation and general experimental J-V data was excellent, using only variations of acceptor (N_a) and recombination center (N_r) densities, and back-contact barrier height (fl_{bc}).

This paper reports AMPS simulation of a group of CdTe cells fabricated at NREL by D. Albin and L. Hasoon and measured at Colorado State University by J. Sites and A. Pudov. These cells underwent various degrees of stress, giving a sequence of J-V curves ranging from normal behavior to severe roll-over. Experimental carrier density profiles (by C-V) were also incorporated into the modeling. The results elucidate the role of changes in fl_{bc} and other properties on cell performance resulting from stressing.

2. PROCEDURE

The J-V characteristics and carrier density measurements (by C-V) of the experimental cells (N2A, N2B, N2C, and F-124-4) were similar and N2C, stressed at maximum power, was chosen as a representative for this set of simulations.

Many of the modeling parameters are generally accepted values taken from the literature (band gaps, mobilities, electron affinities, optical absorption coefficients, densities of states, permittivities, and the $CdS_xTe_{(1-x)}$ thickness and band gap). Another group [carrier densities and thicknesses of the front two layers of the CdTe (1.7e14 and 3e14 cm^{-3}) and CdS, and total CdTe layer thicknesses] were taken from measurements on these particular cells. Finally, another group of variables was used as fitting parameters. These included carrier density and thickness in CdTe layer 3, acceptor energy level, and recombination center parameters (N_r, E_r, σ_n, σ_p) in all the CdTe layers, and the back contact barrier height. The baseline cell parameters are shown in Table 1 and a band diagram is shown in Fig. 1.

Table. 1. Baseline (unstressed) case parameter set.

	n-CdS	p-$CdS_xTe_{(1-x)}$	p-CdTe 1	p-CdTe 2	p-CdTe 3
Eg (eV)	2.42	1.46	1.5	1.5	1.5
Nd (cm^{-3})	1e17				
Na (cm^{-3})		1.7e14	1.7e14	3e14	1e16
x (m)	0.1	0.1	2	1.1	9.7
Nr (cm^{-3})	1.7e15	1.7e15	1.7e15	1.7e15	1.7e15
Er (eV)	1.21	0.75	0.75	0.75	0.75

σ_n = 1e-12 cm^{-2} and σ_p = 1e-12 cm^{-2} for all CdTe layers

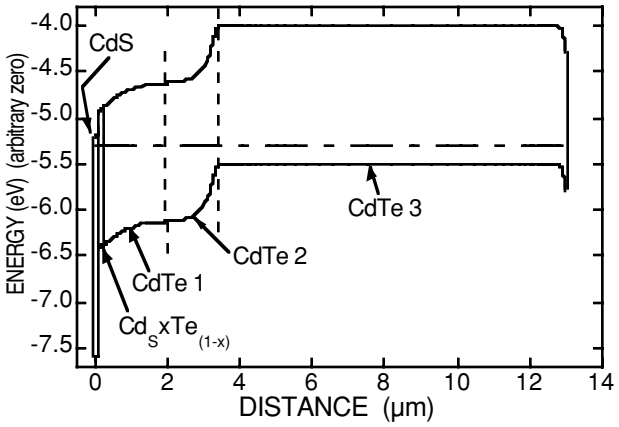

Fig. 1. Baseline simulation cell band diagram (dark, 0 bias).

The recombination parameters and the carrier density in CdTe layer 3 (N_{a3}) were varied until a good match was obtained between the V_{oc}, ff, and J_{sc} of the experimental cell and those of the simulation. A value of flbc = 0.47 eV gave the best fit for the unstressed cell, tilting the high forward bias curve slightly but having only a small effect on ff.

3. RESULTS

J-V Data Comparison

Excellent agreement was obtained for the entire light J-V curve between the unstressed experimental data and the baseline simulation as shown in Fig. 2. Although this could be expected since the J_{sc}, V_{oc}, and ff points of the simulation were matched to those of the experimental cell (N2C), the agreement with the rest of the curve, particularly the change of J_L with V and the portion for $V > V_{oc}$, is remarkable. Variation of the CdTe 3 layer thickness from $x_{CdTe,3}$ = 0.7 to 9.7 m yielded identical J-V curves; the thickness of that layer makes no difference to the operation of the cell until it starts to be depleted at $x_{CdTe,3}$ < ~ 0.2 m

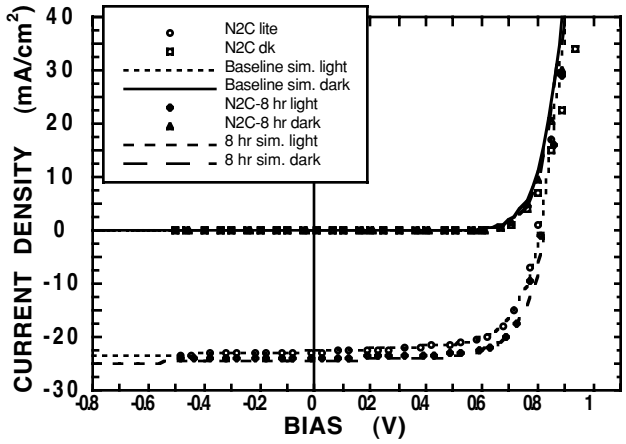

Fig. 2. Experimental J-V (points) compared with simulated curves (lines) for unstressed and 8 hr stressed cells.

and then V_{oc} and ff decrease. The agreement between the dark curves is not as good. This may be related to photoionization of the recombination and dopant centers occurring in real cells, whereas AMPS cannot simulate this.

After 8 hr of stress at the maximum power point, the cell showed a noticeable increase in J_{sc} and V_{oc}. Reducing N_r from the baseline 1.7e15 to 1.0e15 cm^{-3}, gave excellent agreement (Fig. 2).

For the remaining stress values, the simulation was modified only by changing fl_{bc} relative to the baseline values. Agreement was qualitative as shown in Fig. 3. This also is not too surprising, considering the model is one dimensional and does not consider grain boundaries nor the leakage paths where the grain boundaries and the back contact intersect. The experimental curves show less saturation for $V > V_{oc}$ than do the simulated ones. Most real Schottky diodes do not saturate in the reverse direction (even for Si and GaAs single crystals), particularly low quality ones with low barriers, whereas theoretical (and AMPS simulated ones) do saturate. The difference has been ascribed to defects, low resistance paths, and edge effects. The overestimation of the ff probably is due to stress induced changes in N_a and N_r in CdTe layers 1 and 2, which have not yet been modeled.

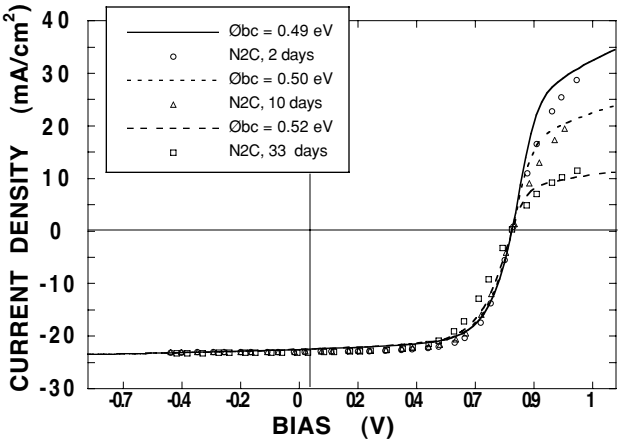

Fig. 3 Experimental cell J-V (points) compared with simulated curve (lines) for selected stressed cells.

Rollover mechanism

Data for total recombination rate (U) for otherwise identical cells with back contact barrier heights of 0.45 and 0.55 eV are shown in Fig. 4. The 0.45 eV cell has normal J-V curves with almost no rollover, while the 0.55 eV cell has severe rollover and some decrease in ff (0.666 vs. 0.625). They

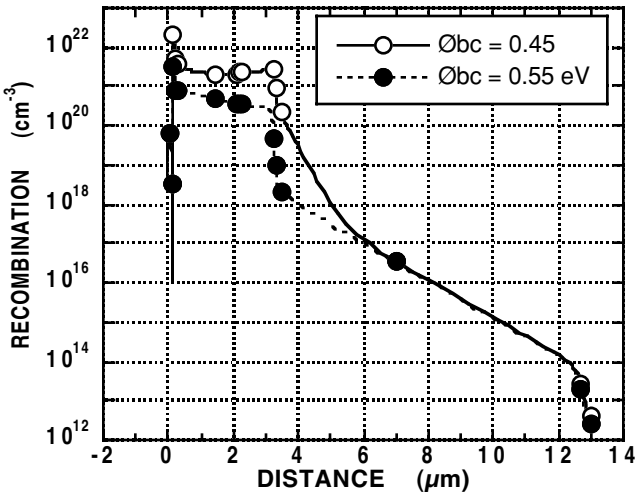

Fig. 4. Simulated recombination vs. distance.

have identical V_{oc} and very similar J_{sc}. the cells are forward biased at 1.1 V, in the rollover region. It appears that almost the entire difference in U is in CdTe layers 1 and 2, with almost no difference in U near the back contact. The back barrier controls the supply of holes which recombine in the 3.7 m of the CdTe nearest the CdS. Thus the rollover mechanism has two interacting parts: control of hole flow by the back contact and recombination near the main junction.

Plots of carrier density vs. x also show major differences in the 0.1 to 5 m region but almost no differences in the 5 to 13 m region. The J_n and J_p vs. x plots show that virtually all the current in 5 to 13 m region is carried by holes, 136 (3.4) mA/cm^2 for the 0.45 (0.55) eV cell. The relatively highly doped CdTe 3 layer is an effective barrier for electrons until $x_{CdTe,3}$ is reduced to zero, when the current at the back begins to be carried by both electrons and holes.

Contact activation energy

Since the back contact controls the hole current for flbc > 0.45 for this baseline series, varying the simulation temperature and plotting hole current at the back of the cell at 1.1 V forward bias vs. 1/T yielded an activation energy fl_{bc} = 0.473 eV. The barrier height value put into the model was fl_{bc} = 0.47 eV, showing consistancy. This may be compared with fl_{bc} = 0.3 eV measured on experimental CdS/CdTe cells by the Institute of Energy Conversion.[4]

4. DISCUSSION

As with any simulation, these results may not represent a unique set of input parameters. The input parameters were chosen to be quite reasonable, except perhaps for the rather large carrier density of the CdTe 3 layer (Na3). However, reducing its thickness $x_{CdTe,3}$ to only ~ 0.2 m with virtually no change in the PV parameters did give some confidence in the choice of Na3. Similarly, Na_3 could be reduced to 3e15 with very little change in the PV parameters. (N_{a3} must be larger than N_r however or bad things happen.) Perhaps the largest set of unknowns are the recombination center properties (N_r, E_r, σ_n, σ_p). Although reasonable values were used here, there is very little experimental information available. One donor-type recombination center was used here; construction of models with several centers would become hopelessly complex and increase the possibility of non-unique parameter sets. Indeed, the level of complexity of a one-dimensional model discourages the assembly of a 2 or 3 dimensional model, unless considerably more recombination center data can be obtained.

5. CONCLUSIONS

AMPS simulation of these experimental CdTe cells yields excellent quantitative agreement with short stress light J-V curves by changing only fl_{bc} and N_r. Reasonably good qualitative agreement with all dark J-V curves and light J-Vs for cells stressed for longer times is obtained by changing only fl_{bc} over a surprisingly narrow span, 0.47 to 0.52 eV.

For these cells, with relatively high doping in the back of the CdTe, the rollover mechanism has two interacting parts: (a) back contact control of hole flow toward the front and (b) recombination there with electrons injected from the CdS.

6. REFERENCES

1 A. Fahrenbruch, NCPV Program Review (1998), AIP Conf. Proc. 462, p. 48.

2 Modeling results obtained using AMPS-1D (Version 1,0,0,1), written under the direction of S. Fonash, Pennsylvania State University, and supported by EPRI.

3 T. McMahon and A. Fahrenbruch Proc. 28th IEEE Photovoltaic Spec. Conf. (2000) p. 539. Also A. Fahrenbruch and T. McMahon, National CdTe R&D Team Meeting , January 25-26, 2001, Golden, CO.

4 NREL Subcontractor Report 520-27929, Institute of Energy Conversion, dated 2/00, p. 39.